

# Quantum frequency downconversion experiment

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We report the first quantum frequency downconversion experiment. Using the difference frequency generation process in a periodically poled lithium niobate waveguide, we successfully observed the phase-preserved frequency downconversion of a coherent pulse train with an average photon number per pulse of  $<1$ , from the  $0.7\text{-}\mu\text{m}$  visible wavelength band to the  $1.3\text{-}\mu\text{m}$  telecom band. We expect this technology to become an important tool for flexible photonic quantum networking, including the realization of quantum repeater systems over optical fiber using atom-photon entanglement sources for the visible wavelength bands.

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Quantum frequency conversion [1] has been attracting attention as a way to connect photonic quantum information systems with photons of various wavelengths. Quantum frequency *upconversion* has been employed to convert a telecom-band photon to a visible wavelength photon, so that single photon detector technologies can be utilized for the visible wavelength bands [2–4]. These “upconversion detectors” have been used for several applications including phase-preserved qubit conversion [5], quantum key distribution [6, 7], and photon-counting optical time domain reflectometry [8]. Also, an erasure of frequency distinguishability between two single photons was demonstrated using upconversion [9].

However, to the best of our knowledge, the frequency *downconversion* of a single photon has not yet been realized. With quantum frequency downconversion (QFDC), we can add further flexibility to networking quantum information systems over optical fiber. For example, we can realize quantum repeater systems [10] based on Duan-Lukin-Cirac-Zoller (DLCZ) [11] or Simon-Irvine (SI) schemes [12] over optical fiber using atom-photon entanglement sources in the visible wavelength bands. A configuration for creating entanglement between two distant atomic states, which is called an “elementary link” in a quantum repeater system based on nested entanglement swapping [10], is shown in Fig. 1. This link includes two independent atom-photon entanglement sources. A visible wavelength photon from a source, whose state is entangled with the internal state of the atom, is frequency-converted to the telecom band by using QFDC. The photons from the two sources are transmitted via fibers to an intermediate node where a Bell state measurement (BSM) is performed using linear optics. As a result, we can establish an entanglement between two atomic states when the BSM is successful. Since several schemes for generating atom-photon entan-

glement have already been demonstrated in the visible wavelength band [13–15], the introduction of QFDC enables us to construct a quantum repeater over optical fiber networks with currently available technologies.

In this paper, we report the first QFDC experiment. Using the difference frequency generation (DFG) process in a periodically poled lithium niobate (PPLN) waveguide, we successfully demonstrated the phase-preserved QFDC of attenuated coherent pulses from the  $0.7\text{ }\mu\text{m}$  band to the  $1.3\text{ }\mu\text{m}$  telecom band.

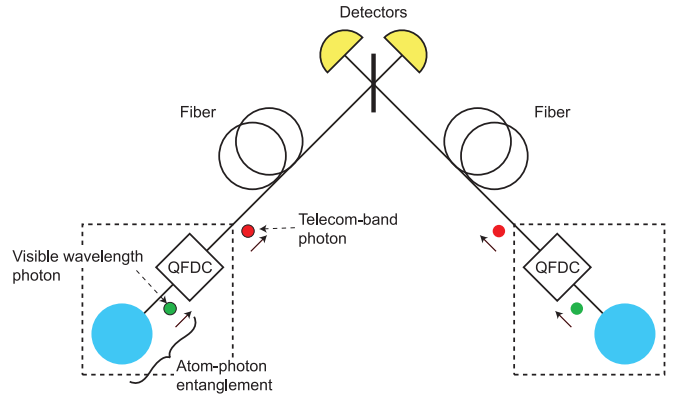


FIG. 1: Elementary link for quantum repeater system based on DLCZ or SI schemes.

Let us briefly describe the theory of the QFDC. We denote the angular frequencies of the pump, the signal and the converted photons as  $\omega_p$ ,  $\omega_s$  and  $\omega_c$ , respectively, which satisfies an energy conservation relationship:  $\omega_p + \omega_c = \omega_s$ . We input a pump light and a signal photon into a  $\chi^{(2)}$  nonlinear medium. When the wavevectors of the signal, pump and converted photons satisfy the phase matching condition, a DFG process involving the three photons occurs in the medium. On the assumption that the pump is strong, the DFG interaction Hamiltonian is given by

$$\hat{H} = i\hbar\chi(a_s a_c^\dagger - H.c.), \quad (1)$$

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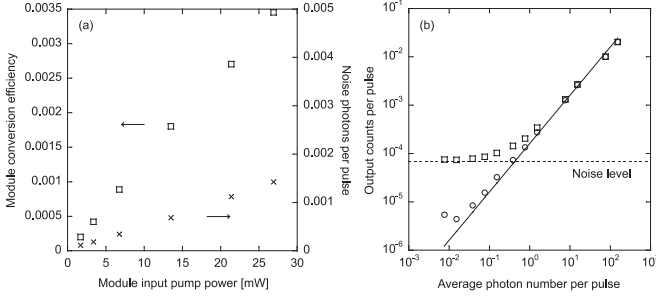


FIG. 4: (a) Conversion efficiency as a function of pump power, (b) output count rate per pulse as a function of average input photon number per pulse.

ratio. The obtained downconversion efficiency as a function of the  $1.5\text{-}\mu\text{m}$  pump power is plotted by squares in Fig. 4 (a). Here, the efficiency is defined as the number of  $1.3\text{-}\mu\text{m}$  photons at the waveguide output divided by the number of  $0.7\text{-}\mu\text{m}$  photons input into the WDM coupler, and so the WDM coupler loss and the coupling loss between fiber and the waveguide are included. We obtained a maximum conversion efficiency of 0.35% for a pump power of 27 mW. We also observed a linear increase in the noise count when we increased the pump power with the signal turned off. The estimated number of noise photons per pulse as a function of pump power is shown by the crosses in Fig. 4 (a). The main origin of this noise was the imperfect suppression of the  $1.5\text{-}\mu\text{m}$  pump by the WDM couplers. However, about 20% of the noise photons probably had other origins, such as a spontaneous Raman scattering process pumped by the  $1.5\text{-}\mu\text{m}$  light in the PPLN waveguide or the fiber pigtail.

To confirm the frequency downconversion of the single photons, we changed the  $\mu$  value and measured the output count rate. The count rate per pulse as a function of  $\mu$  is shown by the squares in Fig. 4 (b). Here, we set the pump power at 27 mW, corresponding to a 0.35% conversion efficiency. The solid line shows the linear fitting, indicating that high-fidelity single-photon downconversion was successfully obtained without correction when  $\mu$  was  $\sim 1$  or larger. The dotted line shows the count rate without the signal ( $\sim 7 \times 10^{-5}$ ), which includes the counts caused by noise photons and the detector dark counts. Clearly, the observed counts deviated from the linear fitting because of the noise counts when  $\mu < 1$ . However, when we subtracted the noise counts, the counts fitted very well even when we set  $\mu \sim 0.01$ , as shown by circles in Fig. 4 (b). This result suggests that we successfully realized the frequency downconversion of an attenuated pulsed light whose average photon number was much less than 1.

Next, we confirmed the realization of phase-preserved downconversion at the single-photon level. We set the conversion efficiency at 0.35%, and changed the signal phase modulation value  $\phi$ . Here, the count rate without the signal was reduced to  $\sim 3 \times 10^{-5}$ , because the PLC interferometer for the  $1.3\text{-}\mu\text{m}$  band suppressed the  $1.5\text{-}\mu\text{m}$

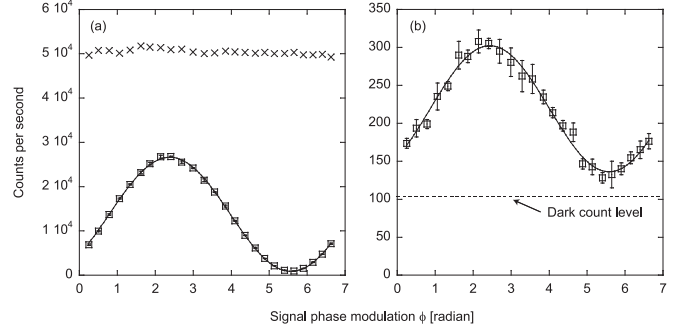


FIG. 5: Count rates per second as a function of signal phase modulation  $\phi$  (a)  $\mu = 143$ , (b)  $\mu = 0.7$ .

$\mu\text{m}$  light by  $\sim 12$  dB, and thus the residual  $1.5\text{-}\mu\text{m}$  noise photons were reduced significantly. The detector count rate was observed as a function of  $\phi$ , while the phase difference induced between the two arms of the interferometer was fixed throughout the measurement. The squares in Fig. 5 (a) show the observed count rate per second as a function of the signal phase modulation value  $\phi$  for  $\mu = 143$ . We obtained clear sinusoidal modulation with a 94% visibility, which demonstrates that the phase modulation applied to the  $0.7\text{-}\mu\text{m}$  signal was transferred to the  $1.3\text{-}\mu\text{m}$  downconverted light. To rule out the possibility that the changes in the count rates were caused by an unwanted intensity modulation, we removed the interferometer and the PC, and undertook the same measurement. We found no intensity modulation in the result shown by the crosses in Fig. 5 (a). We then undertook another fringe measurement with a reduced  $\mu$  value of 0.7. The result is shown in Fig. 5 (b), which again shows a clear sinusoidal modulation. The fringe visibility was  $37.9 \pm 1.1\%$ , which was mainly limited by the detector dark count ( $2.6 \times 10^{-5}$  per gate, corresponding to 104 Hz with a 4-MHz gate). When we subtracted the detector dark counts, the fringe visibility was  $72.1 \pm 2.2\%$ , indicating that we can obtain a reasonable fidelity if we use a single photon detector with a smaller dark count rate, such as a superconducting single photon detector (SSPD) [17]. Thus, we successfully confirmed the realization of phase-preserved QFDC with attenuated pulsed lights where  $\mu < 1$ .

We then undertook fringe measurements with several  $\mu$  values. The obtained fringe visibility as a function of  $\mu$  is shown by the squares in Fig. 6. The solid line shows the theoretical curve that takes account of the signal-to-noise ratio degradation caused by the dark counts and noise photons. We managed to observe fringes with  $\mu \geq 0.09$ . The circles show the visibilities after the subtraction of the detector dark counts. This result suggests that, although the use of a low-noise detector significantly improve the visibility, the residual noise photons limit the fidelity in the present experiment.

The above result indicates that we need to improve the signal-to-noise ratio of the QFDC process to realize better fidelity. In addition, to apply this technique to

quantum information systems, we need to increase the conversion efficiency significantly. The relatively small conversion efficiency observed in the above experiments was mainly attributed to the multimodal characteristics of the PPLN waveguide for the  $0.7\text{-}\mu\text{m}$  light: since the waveguide is not single mode at visible wavelengths, only a fraction of the input  $0.7\text{-}\mu\text{m}$  signal was coupled to the fundamental mode, which effectively reduced the coupling efficiency between the fiber and the waveguide. A solution to this problem is reported in [18], where a mode filter and an adiabatic taper are fabricated on a PPLN chip so that a  $0.78\text{-}\mu\text{m}$  light is efficiently coupled to the PPLN waveguide. By utilizing a similar technique, we can expect significant improvements in both conversion efficiency and signal-to-noise ratio.

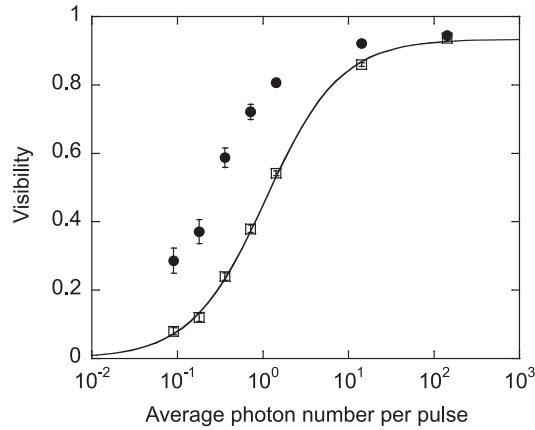


FIG. 6: Fringe visibility of the single photon interferences obtained with the downconverted photons as a function of average photon number per pulse. Squares: with raw data, circles: after subtraction of detector dark counts.

In conclusion, we successfully demonstrated the QFDC of a single-photon-level light from the  $0.7\text{ }\mu\text{m}$  band to the  $1.3\text{ }\mu\text{m}$  band. We obtained a downconversion efficiency of 0.35% with a 27 mW pump power, and also confirmed phase-preserved QFDC. We expect that this technology will be useful for the flexible networking of quantum information systems over optical fiber.

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